

1 Introduction

The Hengduan Mountains lie in the north of the Mountains of Southwest China biodiversity hotspot, the most biologically diverse temperate ecosystem in the world (Conservation International, 2008), sandwiched between the Honghe Basin to the east and the Qinghai-Xizang Plateau to the west. They comprise five main ridge systems characterized by vertical vegetation zonation and separated by four deep drainage systems, created during the Himalayan orogeny beginning in the Tertiary Period and continuing into the Quaternary (Myers et al., 2000; Ying, 2001). The floristic diversity of the region is particularly high: the Hengduan Mountains are situated in Yunnan Province which, despite covering just 4 % of China's land area, contains ca. 15 000 species of higher plants, almost 50 % of the country's total.

The marked altitudinal zonation of vegetation in the Hengduan Mountains offers the potential to compare between sites and build up an understanding of how this zonation arose and how it responds, through time, to climate change and human impacts. The Jade Dragon Snow Mountain (rising to 5596 m a.s.l.) is one of the highest peaks in the Hengduan Mountains region, and is particularly appropriate for the study of past and present diversity using palynological data because it supports a number of natural wetlands and lakes containing abundant, well-preserved palynomorphs, at a range of altitudes. Thus, sampling of core sediments from different sites has the potential to generate pollen data relative to both time and altitude (at a given locality), which will ultimately enable us to estimate changes in both floristic composition and diversity over time and their response to climatic change.

During the past decade, pollen analysis has been employed extensively for understanding Quaternary vegetation and climate history in China (e.g., Xu et al., 2002; Xiao et al., 2004; Zhao et al., 2007; Li et al., 2011; An et al., 2013; Cao et al., 2013; Jiang et al., 2013). However, few such studies have been conducted in the Hengduan Mountains (Jiang et al., 1998; Shen et al., 2006; Jones et al., 2012; Song et al., 2012; Cook et al., 2013; Xiao et al., 2014). Previously, in this series of studies, we investigated

13435

changing climate and vegetation over the past 9300 years based on pollen analyses of a core 400 cm in depth from a wetland site at Haligu (3277 m) on the Jade Dragon Snow Mountain (Song et al., 2012). This paper in the series presents a 22 570 yr record of vegetational and climatic change from Wenhai Lake (3080 m), also on the Jade Dragon Snow Mountain. We aim to use pollen data to develop insights into the changing floristic diversity of the region during the Late Quaternary. This data will also be used to draw inferences about past climate and anthropogenic influences, and to compare study sites at different altitudes in the region to provide a better understanding of changes in the distinctly vertical vegetation zones that characterize the region.

2 Study area

Wenhai Lake (26°58'59" N, 100°09'54" E) is located at the southern end of the Jade Dragon Snow Mountain in Yulong County of Lijiang City, northwestern Yunnan, Southwest China (Fig. 1). It forms part of Lashihai Swamp Natural Reserve and is about 23 km northwest of Lijiang City. This area is a key region linking the Qinghai-Xizang Plateau with the Yungui Plateau, and also is a boundary region between the Hengduan Mountains area of northwestern Yunnan and the plateau area of eastern Yunnan. More than a thousand years ago, Wenhai was an important stop on the ancient "Tea-Horse Road," a route for trading tea and horses between inland agricultural and remote nomadic regions (Luo, 2003). Yulong County is home to several ethnic minority peoples, with the Naxi being most numerous. Wenhai Lake is an open lake surrounded by high mountains, covering an area of about 0.16 km². It is a seasonal lake fed mainly by rainfall and glacial melt-water from the nearby mountains.

The study area is strongly influenced by the southwest monsoon coming from the Indian Ocean. Thus the summers are warm and humid and the winters cool and dry. The mean annual temperature and precipitation measured at Lijiang (situated below the study site at about 2200 m), are 12.8 °C and 935 mm, respectively. About 90 % of the annual precipitation falls in summer, between June and October. The warmest

13436

ern pollen slides, palynological literature and monographs (IBCAS, 1976; IBSCIBCAS, 1982; Wang et al., 1995). All samples yielded abundant, well-preserved palynomorphs. Pollen samples were examined using a Leica DM 2500 light microscope at a magnification of 400 × and at least 300 pollen grains and spores were counted in each sample. Pollen grains and spores were divided into four categories: trees and shrubs, herbs, pteridophytes and aquatic taxa. Pollen data were expressed as percentages and graphed using Tilia.Graph, and pollen zones were determined with CONISS in the Tilia program (Grimm, 1997).

4 Results

4.1 Chronology

Two AMS radiocarbon dates, $14\,075 \pm 40$ yr BP (17 150–16 350 cal. yr BP) at depth of 155 cm and $19\,075 \pm 50$ yr BP (22 760–22 380 cal. yr BP) at depth of 320 cm, give a relatively reliable basis for establishing a chronological control against which to decipher the vegetation and climate history in and surrounding Wenhai Lake. The sedimentation rates are ca. 0.1 mm yr^{-1} and 0.28 mm yr^{-1} for the depths of 0–155 cm and 155–320 cm, respectively. Ages of other depths are interpolated by assuming that the sedimentation rate is constant between the two dated samples.

4.2 Pollen analysis

4.2.1 Surface samples

Fifty palynomorphs were identified from the six surface soil samples collected in close proximity to the core, including 29 families and seven genera of angiosperms, three genera of gymnosperms, nine families and one genus of pteridophytes, and one genus of alga (see the Supplement). The palynomorphs were summed into four groups: conifers, broad-leaved plants, ferns and aquatics. Coniferous trees include *Pinus*, *Abies*

13439

and *Tsuga*. The broad-leaved taxa comprise angiosperm trees, shrubs and herbs, including *Quercus*, *Alnus*, *Artemisia*, Cyperaceae, Ericaceae and Polygonaceae. The ferns include Polypodiaceae, Athyriaceae and *Pteris*. The aquatic plants are *Myriophyllum* and *Zygnema*. The pollen assemblage is dominated by coniferous taxa, at percentages ranging from 66.8% to 93.5%, followed by broad-leaved elements (5.3–16.8%), ferns (0.9–15.3%) and aquatics (0–3.0%). *Pinus* pollen (63–88.5%) dominates in all six surface samples, accompanied by *Abies* (3.3–11.1%), Polypodiaceae (0–10.6%), *Quercus* (1.2–5.6%), Ericaceae (0–4.1%), Athyriaceae (0.2–2.8%), Polygonaceae (0.2–2.4%), Cyperaceae (0–1.1%), and Gramineae (0–0.3%). This pollen assemblage is consistent with the local vegetation of the lake basin and the surrounding mountains, reflecting a needle-leaved forest dominated by *Pinus* and accompanied by some broad-leaved components, e.g. *Quercus* and Ericaceae.

4.2.2 Pollen diagram zonation and description

Pollen analysis of the core samples shows a high degree of taxonomic diversity. The palynoflora comprises 83 palynomorphs, which can be identified to 45 families and 13 genera of angiosperms, one family and seven genera of gymnosperms, 12 families and three genera of pteridophytes and two genera of algae (see the Supplement). Some of the selected palynomorphs extracted from the core are illustrated in the Supplement.

A greater diversity of palynomorphs was recovered from the core samples than from the surface samples, which might suggest that surface samples fail to capture the local vegetation completely. However, many of the taxa found in the core but missing from surface samples are not present in the upper part of the core and are no longer present in the immediate area so do not contribute to the local pollen rain. Examples include *Cedrus*, *Dacrydium* and *Taxodium* amongst the gymnosperms and the angiosperm taxa Actinidiaceae, Anacardiaceae, *Carpinus*, Clethraceae, Flacourtiaceae, Icacinaceae, Juglandaceae, *Liquidambar*, Myrsinaceae, Palmae and *Tilia*. Some of these taxa have a subtropical distribution and their closest occurrence to the study site is at much lower elevation near the Jinsha River or considerably further south

13440

The period between 21 140 and 19 350 cal. yr BP (Pollen zone 2) was marked by a notable increase in aquatic pollen and a continuing dominance of broad-leaved trees in the pollen sum of trees and shrubs. In addition, *Alnus* was found for the first time, while Polygonaceae and Athyriaceae showed a slight increase. This pollen assemblage suggests that the vegetation was dominated by broad-leaved forest as before, accompanied by needle-leaved forest, indicating a relatively warm and moderately humid climate condition with several climatic fluctuations during the period.

From 19 350 to 17 930 cal. yr BP (Pollen zone 3), the coniferous trees *Pinus* and *Abies* showed a distinct increase, with *Abies* especially reaching its maximum proportion during this period. In contrast, broad-leaved *Quercus* displayed a remarkable decrease compared to the last stage. *Tsuga*, *Alnus*, Polygonaceae, Athyriaceae, *Myriophyllum* and *Pediastrum* were still visible, but their percentages gradually declined. This pollen assemblage reflects a transition from broad-leaved forest to needle-leaved forest. The climate of the period was warm and humid at the beginning, but shifted to cold and dry at the end.

Between 17 930 and 9250 cal. yr BP (Pollen zone 4), coniferous and broad-leaved trees dominated alternately to begin with, but coniferous trees become predominant by the end. This implies that the climate fluctuated between warm-humid and cold-dry, as evidenced by decreases and increases in conifers and *Quercus*, as well as the discontinuous occurrence of *Tsuga*, *Liquidambar*, Polygonaceae, Cyperaceae, *Myriophyllum*, *Pediastrum* and pteridophytes.

From 9250 cal. yr BP to the present day (Pollen zone 5), *Pinus* underwent a process of decrease at the depth of 50–80 cm (from 38.1 % to 14 %), increase from 30 to 50 cm (from 14 % to 56.8 %, this shows a trend consistent with the Haligu core between 4000–2400 cal. yr BP), and decrease again at 0–30 cm (from 56.8 % to 14.5 %), while *Tsuga* displays an opposite trend. *Abies* shows a distinct increase during this period. *Quercus* increased at the beginning of the stage, then decreased after that. The drought-tolerant herb *Artemisia* had a very low percentage. The hygrophilous herb Polygonaceae and fern Polypodiaceae experienced an increase, decrease and increase. This pollen as-

13445

semblage indicates that the vegetation was dominated by needle-leaved forest (comprising mainly *Pinus* and *Abies*), coupled with broad-leaved forest (mainly *Quercus* and *Betula*), reflecting a transitional climate condition from warm-humid to cold-humid.

5.2 Palynological signals of human activity detected in the Wenhai core

Based on pollen and other evidence, human influences on postglacial vegetation have been inferred in Europe and North America (e.g., Brugam, 1978; Hiron and Edwards, 1986; Smith and Cloutman, 1988; Russell et al., 1993; Parker et al., 2002), as well in China (e.g., An et al., 2002; He et al., 2002; Xu et al., 2002; Song et al., 2012). The present authors published the first of a series of studies covering a range of altitudes within the Hengduan Mountains (Song et al., 2012). The altitude of the previous study site, Haligu, is 3277 m, where there is no current human settlement. The present study area (3080 m), about 2 km far from Haligu, is close to a Naxi ethnic minority settlement at Wenhai village. Moreover, Wenhai was an important stop on the ancient “Tea-Horse Road” (Luo, 2003), making it likely that a wide variety of cultivated plants were introduced into the agricultural system around the lake, as evidenced by an ethnobotanical survey of traditional edible plants (including 45 cultivated plants) used by Naxi people in Wenhai village (Zhang et al., 2013).

In the Wenhai core, several observations may be interpreted in terms of increasing anthropogenic impact in the region. First, *Pinus* and *Quercus* pollen decreased distinctly at the depth of 0–30 cm, which is probably linked with the fact that local people felled the trees for house construction or fuel wood. We detected that *Quercus* pollen decreased steadily in the Haligu core during the period from 2400 cal. yr BP to the present day and observed heavy present-day coppicing of *Quercus* for firewood, resulting in much reduced pollen production. The comparison of both cores may substantiate the existing human impacts in the region. Second, the occurrence of abundant Labiatae pollen also indicates increasing human activity. From our personal observation, the Naxi people in Wenhai village currently cultivate several Labiatae species, including *Perilla frutescens* (L.) Britton and *Mentha* spp. as edible herbs and for medical

13446

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13449

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13450

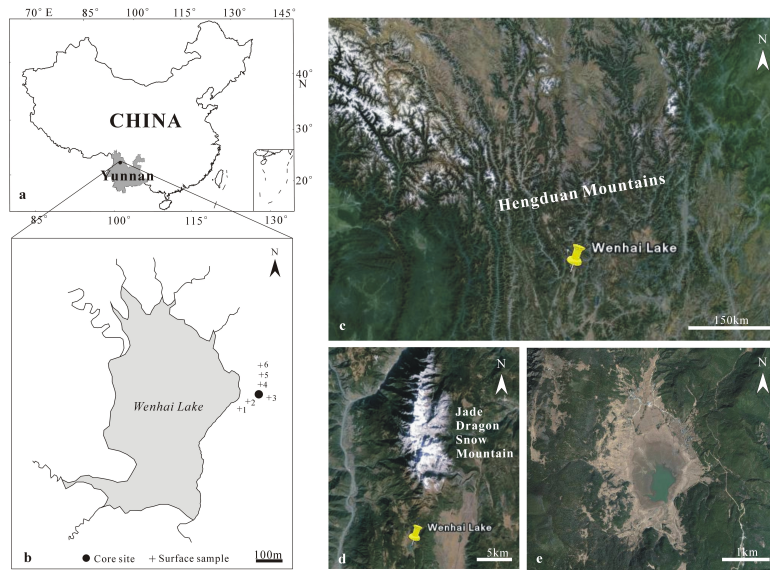


Figure 1. (a) The location of Wenhai Lake in northwestern Yunnan, China, (b) the position of core and surface soil samples, (c) the location of Wenhai Lake in the Hengduan Mountains, (d) the location of Wenhai Lake on the Jade Dragon Snow Mountain, (e) an enlarged photograph of Wenhai Lake (c, d and e are cited from Google Earth).

13451

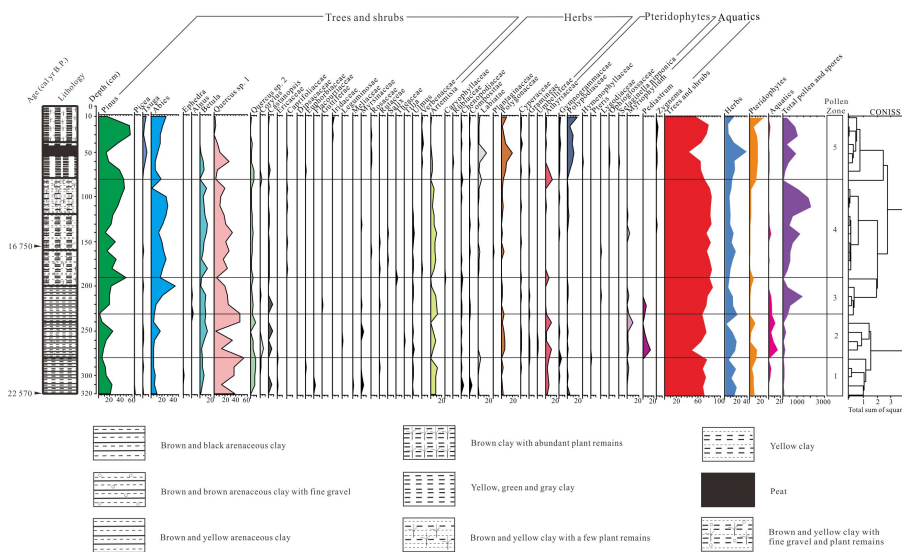


Figure 2. Pollen percentage diagram of selected taxa from Wenhai Lake, northwestern Yunnan, China.

13452

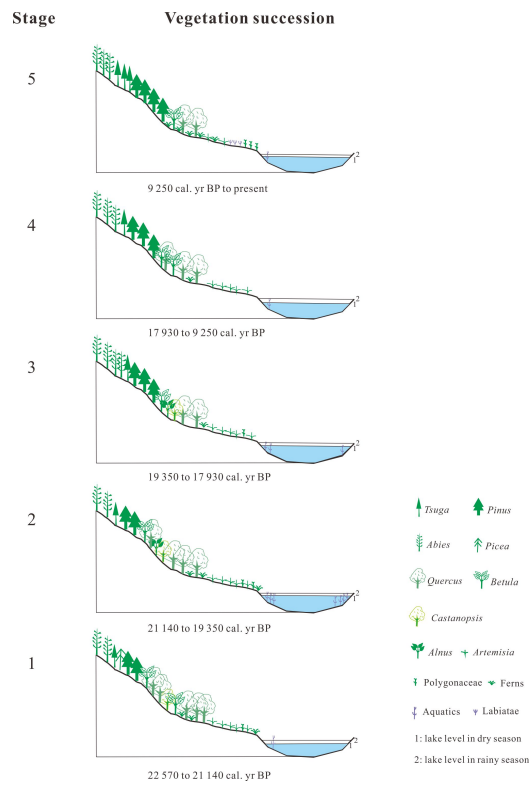


Figure 3. Inferred vegetation succession over the past 22 570 yr at Wenhai.